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Field Experience with Lock Culvert Valves

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INTRODUCTION: The objective of this technical note is to identify lock culvert valve issues that challenge the US Army Corps of Engineers (USACE) as it continues to provide reliable transport at navigation projects. In order to accomplish this objective, navigation projects were visited to observe operations and discuss maintenance history with lock operations and maintenance personnel. The intent was to identify any common troubles that particular valve designs have presented. The personnel interviewed varied from area office engineers to maintenance contractors. Also, pertinent findings from previously published prototype lock studies are included. Particular attention was given to the valves on locks with lifts in excess of 30 ft which are classified as high-lift and very-high-lift locks (Headquarters, USACE 2006), since these projects have historically had the most issues.

PROJECTS: Site visits were made to several USACE locks and two locks operated by the Department of Transportation's St. Lawrence Seaway Development Corporation (SLSDC). The lock valve parameters for the navigation projects visited are listed in Table 1 along with those for which prototype studies have been published (listed in the footnotes following Table 1). These six prototype studies provide data useful for quantitative analysis of valve performance. Information applicable to lock culvert valve design, operation, or maintenance is provided in the following project discussions. A brief description is given for projects, listed by waterway, that had interesting accounts regarding their lock culvert valves.

ST. LAWRENCE SEAWAY

Eisenhower and Snell Locks. The valves on the Eisenhower and Snell Locks, two locks operated and maintained by the SLSDC, are being replaced. The existing values are of double-skin construction. This design has lack of access to interior structural members. They are being replaced with new values of a vertical-frame design to improve the ability for inspection and maintenance of structural members. A photograph of two of the SLSDC valves is provided in Figure 1 in which a vertical-frame valve is in front of a double-skin-plate valve. The double-skin construction wraps structural members such that the valve is *streamlined* because fewer objects are exposed to the flow. However, the semi-circular top and bottom of the valve arms are subject to flow-control oscillations, which in turn tend to vibrate the entire valve. Vibration of the double-skin-plate valves led the SLDC to add lateral dampers (dynamic vibration absorbers). Dampers, attached to the valves, ride against the valve's wall seals as shown in Figure 2. The dampers remedied the vibration problems.

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Table 1. Navigation projects visited or tested.

Lock Project	River/Waterway	Chamber Size, Width and Length, ft	Culvert Width and Height at Valve, ft	Valve Radius, ft	Reverse Tainter Valve Design	Lift, ft
Eisenhower	St. Lawrence Seaway	80 x 860	12 x 14	21.0	DSP	43
Snell	St. Lawrence Seaway	80 x 860	12 x 14	21.0	3 DSP, 1 VF	49
Bankhead[1]	Black Warrior	110 x 600	14 x 14	20.0	VF	69
Holt	Black Warrior	110 x 600	12.5 x 12.5	17.0	VF	64
Melton Hill	Clinch	75 x 400	8 x 10	16.0	VF	54
Cheatham	Cumberland	110 x 800	12.5 x 12.5	18.0	DSP	26
Barkley[2]	Cumberland	110 x 875	16 x 16	24.0	DSP	57
Fort Loudoun	Tennessee	60 x 360	6 x 7	10.7	DSP	70
Watts Bar	Tennessee	60 x 360	6 x 8	10.75	VF	70
Chickamauga	Tennessee	60 x 360	8 x 8	10.58	VF	50
Wheeler	Tennessee	110 x 600	12 x 14	20.5	DSP	48
Wilson	Tennessee	110 x 600	15 x 15	22.0	DSP	94
Kentucky	Tennessee	110 x 600	12 x 12	16.0	DSP	56
Demopolis	Tombigbee	110 x 600	12.5 x 12.5	18.25	PDSP	40
Whitten[3]	Tennessee-Tombigbee	110 x 670	14 x 14	20.0	VF	84
Heflin	Tennessee-Tombigbee	110 x 600	13.5 x 13.5	19.0	VF	36
Bonneville[4]	Columbia	86 x 675	12 x 14	19.5	VF	69.5
The Dalles	Columbia	86 x 675	12 x 14	19.5	DSP	90
John Day[5]	Columbia	86 x 675	12 x 14	19.5	DSP	110
McNary[6]	Columbia	86 x 675	11 x 12	17.0	DSP	92

Note: VF = vertical-frame design, DSP = double-skin-plate design, PDSP = partial-double-skin-plate design

1 Tool (1980)

2 Neilson (1975)

3 McGee (1989)

4 Waller (1997)

5 Neilson and Pickett (1986)

6 US Army Engineer Waterways Experiment Station (1960)

Two, new vertical-frame valves were furnished to the SLSDC in January 2011, and one was installed in the south filling-valve location at Snell Lock. An option for the SLSDC to order six more valves to complete the replacement was delayed because experience with the new vertical-frame valve currently in service revealed certain operational difficulties. Operation of the new valve exerted more load on the operating machinery than the double-skin-plate valve that it replaced, even though the new valve was significantly lighter. A hydraulic model study is currently underway to customize a vertical-frame valve design that meets SLSDC's requirements for hoist loads.

Figure 1. Valves on the Eisenhower and Snell Locks: new vertically framed design in foreground, existing double-skin-plate design in background.

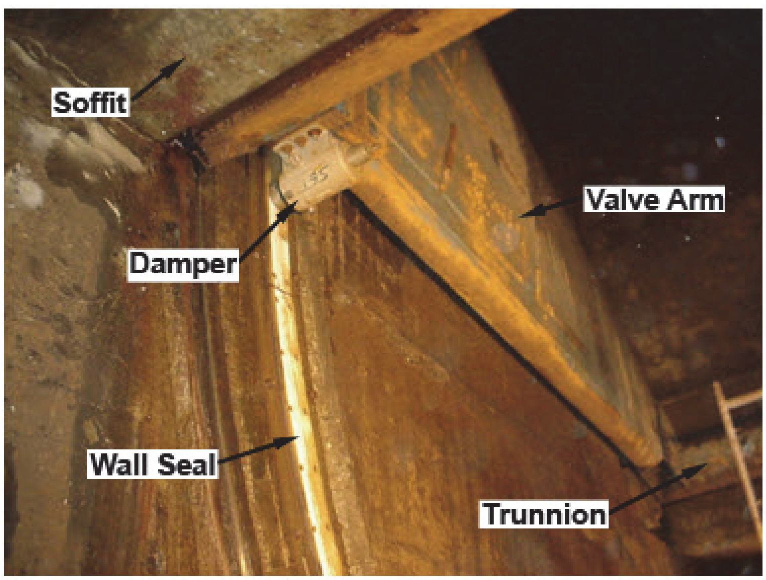

Figure 2. Damper attached to bottom of valve arm, Eisenhower and Snell Locks.

TENNESSEE-TOMBIGBEE WATERWAY

Whitten Lock. A field investigation of Whitten (formerly Bay Springs) Lock was conducted to determine the operating characteristics and hydraulic efficiency of the lock (McGee 1989). The field study evaluated hydraulic design factors pertaining to valves such as the hoist loads, cavitation parameter, and effects of venting.

To reduce the surge in the navigation channel below the lock, the lock is often emptied using a single-valve operation. When a single valve is used for emptying, the pressure downstream of the

emptying valve becomes very low. Regardless, experiments confirmed that dual 12 in. diameter vents are capable of supplying the volume of air demanded during these moments of low pressures (McGee 1989). The valve schedule that is presently used at the project (2 min 15 sec, filling-and-emptying valve opening time) ensures that adequate air is drawn into the culvert to cushion the cavitation implosions (Stockstill 2002). The reverse tainter valves have performed well, and the operating conditions are satisfactory.

BLACK WARRIOR RIVER

Holt Lock. The Holt Lock valves have performed poorly and have been a maintenance problem since the lock began operations in the late 1960s. The lifting mechanisms of the filling and emptying valves vibrate during lock operations. Project personnel indicated the maintenance and repair needs for the filling and emptying valves were similar. The bulkhead covers have been removed to reduce the work required during the frequent valve repairs.

The valve opening schedules have been altered to provide safe lock-chamber performance. A typical filling operation consists of raising the filling valves 25% where they are kept for approximately 8 min before they are fully opened. A faster valve operation has been associated with incidents wherein mooring lines on loaded barges have broken. The valve lifting assemblies shake moderately while the valve is 25% open. However, once the valve resumes opening, the strut, rocker assembly, and cylinder shake and continue shaking even when the valve is fully open. The movement has caused wear on the lifting assemblies and valve seals and trunnion.

During a typical emptying operation, there is slight movement of the valve strut and rocker assembly as the valve is opened. Once the valve is fully open and in the recessed position, noticeable movement of the upper valve strut, rocker assembly, and cylinder can be observed. The connection between the rocker assembly and upper valve strut moves vertically and laterally. Project personnel said this was common and that it causes excessive wear on the valve seals, trunnion connections, and valve strut connections.

A few years ago, the field tested a modified valve. Plate steel was added across the bottom of a valve to stiffen and streamline it. However, the first time it was operated under head, the valve shook violently causing the lock operation house to tremble; the plate steel was removed. This shows that small changes to a valve's shape can have adverse hydrodynamic loading consequences. The USACE, Mobile District (SAM) is in the process of designing replacement valves that are similar to the Bankhead Lock valve.

Bankhead Lock. The Bankhead Lock valves have performed well, and their design is recommended by SAM operations personnel. Regularly scheduled maintenance is currently underway wherein each valve is removed, repaired, and reinstalled. Maintenance crews noticed damage to the downstream side of a valve. When the valve was removed from the culvert, it was found that the skin plate damage was much more extensive than originally thought. The top third of the valve skin plate was removed (Figure 3) and replaced. Evidence of cavitation damage, more common downstream of lock valves, was noticed on the skin-plate steel, which had sharp-edged pits. The location of damage on the Bankhead Lock valve suggests that at certain valve openings, most likely small openings, high-velocity flow passes between the downstream side of the skin plate and the soffit seal.

Figure 3. Replacing upper skin plate on Bankhead Lock valve.

The Bankhead Lock valve design is about 34% heavier than the valve design used at Holt Lock. The valves at both projects are vertically framed with similar spacing between the skin plate and the horizontal girders. A prototype testing program (Tool 1980) measured the hoist loads indirectly by recording the hoist cylinder pressures. The 1 min, single-valve operation cylinder pressures were less than those predicted on the construction drawings, and the pressures with a 2 min, single-valve were 200 to 300 psi less than the 1 min, single-valve operation.

TENNESSEE RIVER

Chickamauga Lock. The lock valves at Chickamauga, Watts Bar, and Fort Loudoun Locks have been a source of operational trouble since they were replaced in the late 1990s. There have been reports of loud noises in the culverts, suggesting cavitation, and valve oscillation during operations. The performance and operational issues have necessitated modification of the operating machinery as well as changes to the valve operation schedules.

Vertical motion of the valve stem during filling indicates that large uplift forces are occurring. Emergency operation simulations, wherein the valve begins closing as soon it reaches fully opened position, result in enough uplift force to trip the lifting mechanism's limit switch. Three modifications have been made to the valve in an attempt to reduce uplift forces. Semi-circular pipes have been installed on the valve arms, plate steel has been placed between the lower horizontal girder and vertical valve ribs, and plate steel has been added between the lower and upper horizontal girders (Figure 4). These modifications have reduced the valve movement during locking operations. A stiffer spring has also been added to the lifting mechanism to increase the limit switch resistance. Side seals provide very little damping on any valve, but lateral dampers installed between the valve and the culvert walls have reduced the vibrations.

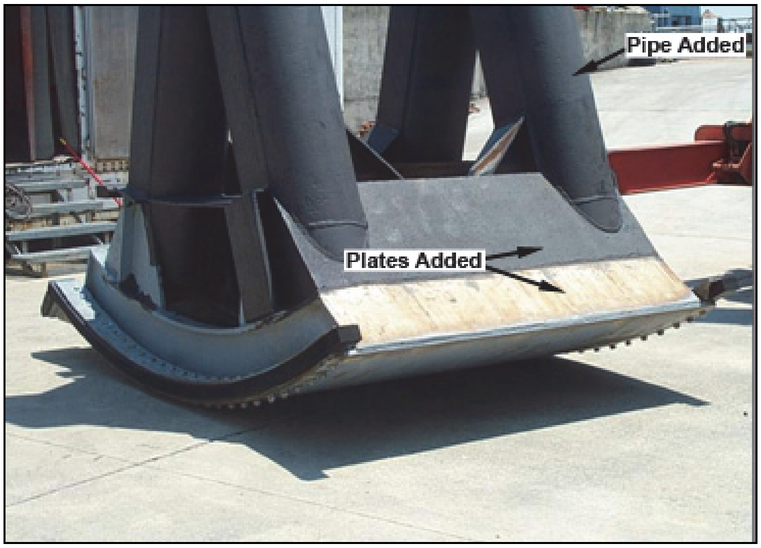

Figure 4. Chickamauga Lock modified valve.

Watts Bar Lock. As mentioned previously, the Watts Bar Lock valves have been replaced with newer valves that are problematic. Lock operations had to be altered from those used with the older valves. Now, filling operations consist of raising the filling valves about 2 ft until the chamber rises 29 ft. This allows the back pressure to build up before the valves are opened further. The valves are then raised approximately 5 ft where they are held until the water surface is just below the upper miter sill. Finally, the valves are lifted to the fully open position. This stepped-valve operation results in a longer filling time. Also, when the valves are held open between 2 and 4 ft, loud noises are produced in the culverts. When the noises occur, the building and lock machinery shake, which suggests that cavitation is occurring. The upper land-side valve was modified in an effort to improve operations, but the noises still occurred when the filling valves were in the mid-range openings.

The lower bulkhead slots on the emptying valves are open to the atmosphere, but the upper bulkhead slots are closed. The open bulkhead slots on the emptying valves may be the reason no booming noises are heard during the emptying operation. The bulkhead covers for the filling valves could be removed to determine if air is being drawn into the culvert during filling. If air is drawn in, it might cushion the cavitation and improve the valve operation.

A physical model has been used to evaluate the performance of the replacement valves (Bislip-Morales and Hite 2013). The model study, which was conducted to determine the valve hoist loads, found that uplift forces could be reduced if the valve's top plate was removed. A horizontal plate installed at the bottom of the valve increased valve hoist loads and valve movement at particular openings.

Kentucky Lock. New replacement valves were constructed for the Kentucky Lock circa 2004 (Figure 5). However, after the problems that had occurred with the replacement valves on Watts Bar Lock, USACE, Nashville District (LRN) believed the risk of having similar problems on Kentucky Lock was too great. The valves sat on a lock wall until a better understanding of why some designs have problems with uplift and vibrations could be found.

Figure 5. Kentucky Lock replacement valves.

CUMBERLAND RIVER

Barkley Lock. The valves of the Barkley Lock have functioned without major operational problems. Field information about this well-performing lock system was obtained during a comprehensive prototype testing program (Neilson 1975). The testing program documented the entire filling and emptying systems but was detailed enough to provide a large volume of information on the lock culvert valves. Pressures at a point on the upstream face and three points on the downstream face of the valve's skin plate were measured. The peripheral, radial, and transverse components of the valve acceleration were recorded. The pressure at the top and bottom of the upstream, land-wall valve hydraulic cylinder were recorded as well as the stress in the lifting rods. The flow rate in the valve air vents was measured, but the rate was too small for any conclusions to be drawn.

Evaluation of the data revealed that the valves are performing as designed and do not experience vibrations. No exciting frequencies were found to be near the valve system's natural frequency. The tests found that pressure fluctuations, strains, and accelerations which might contribute to structural fatigue were relatively low and not likely to be of structural significance. Design forces obtained from a physical model study (Fidelman 1963) were found to agree reasonably well with average, measured lifting rod forces.

COLUMBIA RIVER

Bonneville Lock. Two sets of prototype tests were conducted on the new Bonneville Lock by Waller (1997). The first set was obtained immediately after completion of the lock (March 1993), and the second set was gathered during conditions of low tailwater (September 1993). Pressures were measured downstream of the filling and emptying valves and within the valve-well. Pressure transducers were installed in four of the ladder wells to determine the water-surface elevations in the lock chamber. Additional transducers were installed to monitor upstream and downstream stages. The lock was designed for ideal operation with a 1 min valve time, which is the nominal valve operation time for normal operating conditions. Slower valve times could result in low pressures in the culvert downstream from the valve. Actual valve operation times and valve patterns for each experimental were measured.

Between March and September, the tailwater variations had resulted in a higher lift. During the September experiments, it became obvious that the valve operation time was dependent on the total head across the tainter valve. No changes were made in the valve machinery settings between the two sets of experiments, yet the fastest valve operation times were recorded to be 72 sec with a lift of 49 ft and 100 sec when the lift was 65 ft. Also, the right fill valve had a no-load opening time of 45 sec, but a dual-valve fill test had a valve time of 79 sec, and a right-side, single-valve fill test had a valve time of 96 sec. These differences can only be attributed to increased head during the longer filling time of the single-valve operation. The valves have performed well, and no problems have been mentioned by operations personnel.

John Day Lock. The double-skin-plate valves used on John Day and the Dalles Locks have had cracks form in the steel wrapper plate of the valve members, and their structural performance has been unreliable over the years. A field inspection report reiterated that operation and maintenance of the valves have been difficult since completion of construction (North 2006).

A prototype study of the John Day Lock system was conducted in 1973 (Neilson and Pickett 1986) to investigate shock waves, vibration, and noise in the lock filling system. Lock operation produces noise and vibrations during filling. The pounding noise can be reduced by opening the filling valves in stages. The valve schedules have been changed to open in a stepped fashion. The two-valve filling operation was recommended by Neilson and Pickett (1986), wherein the valves are operated to one-third open in 40 sec, holding at one-third open for a 5 min delay, and opening in 80 sec. Neilson and Pickett (1986) also recommended that a single valve could be operated in a similar schedule with a 10 min delay. While the valves are held at the one-third open position, the flow approaches an average velocity of 60 fps under the valve (Headquarters, USACE 1975).

The USACE, Portland District (NWP) is replacing the valves. A photograph of a new valve taken during fabrication is provided in Figure 6, and one of a completed valve is shown in Figure 7.

Figure 6. New John Day Lock culvert valve during fabrication.

Figure 7. Newly fabricated John Day Lock culvert valve, turned on its side (top is on left).

McNary Lock. McNary Lock experienced thundering noises when the filling valves were partially open. The effects of the pounding at the valve were transmitted to the operating machinery, so the hoist loads were measured. The pounding noise was caused by pockets of air being drawn into the flow through the downstream bulkhead slot, traveling upstream to the low-pressure area immediately downstream of the partially open valve and collapsing. The noise was eliminated when the air vent downstream of the valve was opened. Velocities under the valve were estimated to have been between 55 and 70 fps.

Prototype tests were conducted to determine the causes and effects of the pounding (US Army Engineer Waterways Experiment Station 1960). This testing program was also part of a generalized research effort to obtain information about valving and air venting for high-head locks. Measurements were taken of pressures in the culverts, vibration of the valve and lock wall, the presence of air or water at critical areas, valve openings, lock water-surface elevations, head-loss and contraction coefficients for the valve, and valve operating forces.

Natural frequencies were calculated for the valve system and compared to the frequency of measured vibrations in the hoist rod. None of the computed or observed frequencies were close to the frequency of the audible pounding. Therefore, it was concluded that resonance was not contributing to the pounding since radial and transverse vibration of the valve was at a much higher frequency.

The oil pressures at the top and bottom of the valve-hoist hydraulic cylinder were measured, and the hoist loads were calculated. The pounding at the valve was accompanied by concurrent cylinder pressure and piston-rod force fluctuations.

SUMMARY AND CONCLUSIONS:

This technical note summarizes troubles experienced with lock culvert valves as follows:

a. Problems have arisen at several locks when double-skin-plate valves have been replaced with vertical-frame designs.
b. Attempts to stiffen and streamline vertical-frame valves by adding plates and deflectors have sometimes resulted in violent vibrations during operations or led to valves that cannot be closed under flow.
c. The addition of lateral dampers has reduced vibrations at several locks.
d. The bulkhead seals have been permanently removed on several locks.

Operations personnel have difficulty removing seals and installing bulkheads when valve maintenance is required. This results in valuable time being spent installing bulkheads when the valve is dewatered. Perhaps a faster, less labor-intensive method of placing and removing bulkhead seals should be investigated.

ADDITIONAL INFORMATION: This CHETN is a product of the Repair and Replacement Guidance for Lock Culvert Valves work unit of the Navigation Structures Research Program being conducted at the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Question about this technical note can be addressed to Allen Hammack (601-634-3628; email: *Allen.Hammack@usace.army.mil*) or Tom Hood (865-986-0286; e-mail: *Thomas.E.Hood@usace.army.mil*). For information about the MCNP-Navigation Structures Research Program, contact the Program Manager, Charles E. Wiggins at 601-634-2471, e-mail: *Charles.E.Wiggins@usace.army.mil*. This technical note should be cited as follows:

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